

**NEHRP Site Class and Liquefaction Susceptibility Mapping
of the Charleston Quadrangle, South Carolina**

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Investigations Undertaken

Charleston, South Carolina is the second most seismically active regions in the eastern U.S, after the New Madrid seismic zone. The 1886 Charleston earthquake (moment magnitude, $M_w \approx 7.3$) resulted in \$23 million (1886 dollars) in damages and about 60 deaths. Based on paleoliquefaction studies, Talwani and Schaeffer [1] estimate a recurrence rate between 500 and 600 years for $M \geq 7$ earthquakes near Charleston.

Because shear-wave velocity and penetration resistance are key information for predicting ground shaking and liquefaction, efforts are underway to compile these measurements and other subsurface information from the Charleston area. As part of the first phase of this project, shear-wave velocity (V_s) and Cone Penetration Test (CPT) measurements made by various organizations at 110 investigation sites in the 1:24,000 Charleston quadrangle have been compiled. Shown in Figure 1 are the locations of the 110 investigation sites plotted on the geologic map by Weems et al. [2]. Also shown in the figure are locations of 45 auger hole sites investigated by Weems and Lemon [3]. Of the 110 investigation sites, 60 are sites where V_s measurements were conducted, including 54 sites tested by the seismic CPT method. The other 50 investigation sites are non-seismic CPT sites where no V_s measurements were conducted. It should be noted that some of the plotted test locations shown in the Figure 1 have been refined since the last annual project summary [4]. Updated summary information and available electronic files for these measurements are given in the data report by Fairbanks et al. [5].

In this annual project summary, many of the V_s profiles from the Charleston quadrangle, as well as additional profiles from the greater Charleston area, are separated and analyzed by subsurface geology. Key information considered in the identification of major subsurface geologic units includes: several 1:24,000 geologic maps and auger hole logs available for the greater Charleston area (e.g., Weems and Lemon [3,6]); CPT tip, sleeve and pore pressure measurements; V_s measurements; and geologic interpretations provided in project reports. Only V_s data from sites where sufficient subsurface information is available to identify major geologic units are considered in the analysis.

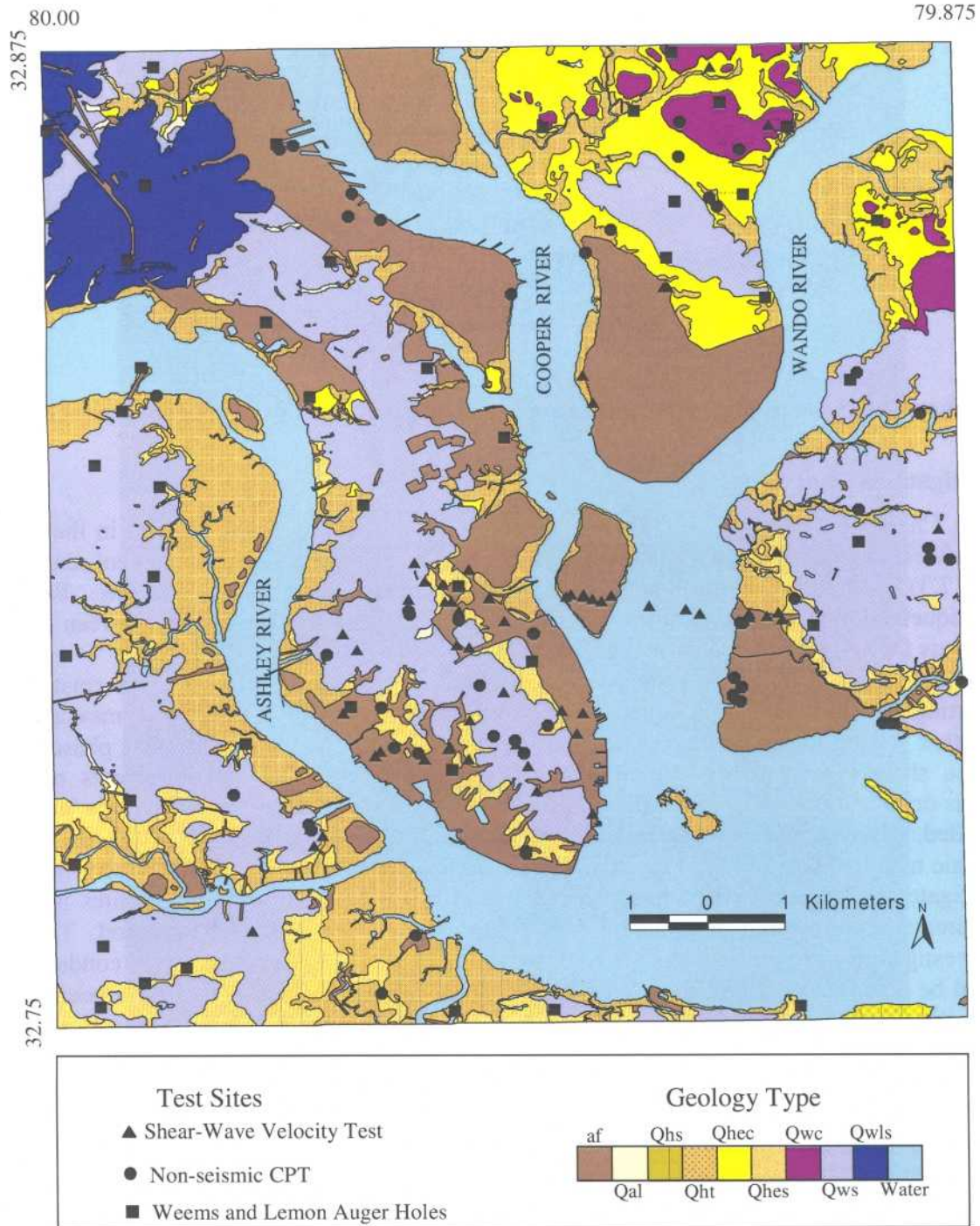


Figure 1: Geologic map of the Charleston quadrangle by Weems et al. (1997) showing locations of V_S and non- V_S investigation sites.

Results

Presented in Figures 2(a)-2(f) are V_S data from 65 investigation sites in the greater Charleston area. The data are grouped by six major geologic units and plotted versus depth. To avoid incorrect V_S assignments, measurements made on the boundaries separating geologic units are not included. Only V_S data measured completely within a unit are used. For the seismic CPT and downhole measurements, at least two data points within a unit at a test site are required for the data to be included in the grouping. The six major geologic units are: 1) fill deposits; 2) Holocene and late Pleistocene deposits; 3) the Wando Formation; 4) the Ten Mile Hill beds; 5) the Penholoway Formation and Daniel Island beds; and 6) the Ashley Formation. A brief description of each unit is given below.

Fill deposits mapped by Weems and Lemon [6] includes artificial fill and phosphate spoil. Artificial fill (af) is less than 300 years old and includes sands or clayey sands of diverse origin, ranging from road fill to other construction fill to non-engineered fill. Phosphate spoil (pf) is less than about 130 years in age, and is material removed and backfilled during phosphate mining. As shown in Figure 2(a), reported values of V_S from the artificial fill and phosphate spoil range between 35 m/s to 325 m/s.

Several different types of Holocene and late Pleistocene deposits are present in the Charleston area [6]. Holocene (<10 ka) deposits include beach to barrier-island sands (Qhs) and tidal-marsh clayey sands and clays (Qht). Early Holocene to late Pleistocene deposits include estuarine silty to sandy clays and quartz sands (Qhec), which range in age from 6 ka to 85 ka. Late Pleistocene deposits include beach to barrier-island sands (Qhes), which range in age from 33 ka to 85 ka. Reported values of V_S from these Holocene and late Pleistocene deposits range from as low as 34 m/s to over 200 m/s, as shown in Figure 2(b).

The Wando Formation is about 70 ka to 130 ka in age. Weems and Lemon [6] identified six facies in the Wando Formation: two clayey sand and clay facies deposited in fluvial to estuarine environments (Qwc, Qwlc), two barrier sand facies (Qws, Qwls), and two fossiliferous shelf sand facies (Qwf, Qwlf). Reported values of V_S from various facies of the Wando Formation are plotted in Figure 3(c). They range from 85 m/s to over 300 m/s.

The Ten Mile Hill beds are approximately 200 ka to 240 ka in age. Weems and Lemon [6] identified three facies in the Ten Mile Hill beds: fluvial and estuarine facies comprised of clays and clayey sands (Qtc), beach to barrier-island facies comprised primarily of well-sorted quartz sands (Qts), and shallow marine shelf facies comprised of fine-grained, fossiliferous and bioturbated sands (Qtf). Plotted in Figure 2(d) are reported values of V_S from the Ten Mile Hill beds. These V_S values range from about 100 m/s to over 300 m/s.

The Penholoway Formation (Qpf) is a fossiliferous sand facies, with age between 730 ka and 970 ka [6]. The Daniel Island beds (Qdc) are clayey sands to clays with similar age, ranging from 730 ka to 1600 ka [6]. Sands in these deposits are often identified in CPT profiles by very high cone tip resistances compared to cone tip resistances measured in overlying and underlying units. Reported values of V_S from the Penholoway Formation and the Daniel Island beds range from about 180 m/s to over 600 m/s, as shown in Figure 2(e).

The Ashley Formation (Ta) was deposited about 28 million years ago (Raymond A. Christopher, personal communication, November 2002). As described by Weems and Lemon [6], the Ashley Formation is a well-compacted, sometimes partially lithified, phosphatic calcarenite. It exists throughout the subsurface in the Charleston area and can be up to 100 m thick. Reported values of V_S from the upper 50 m of the Ashley Formation are plotted in Figure 2(f). These V_S values range from less than 180 m/s to over 700 m/s.

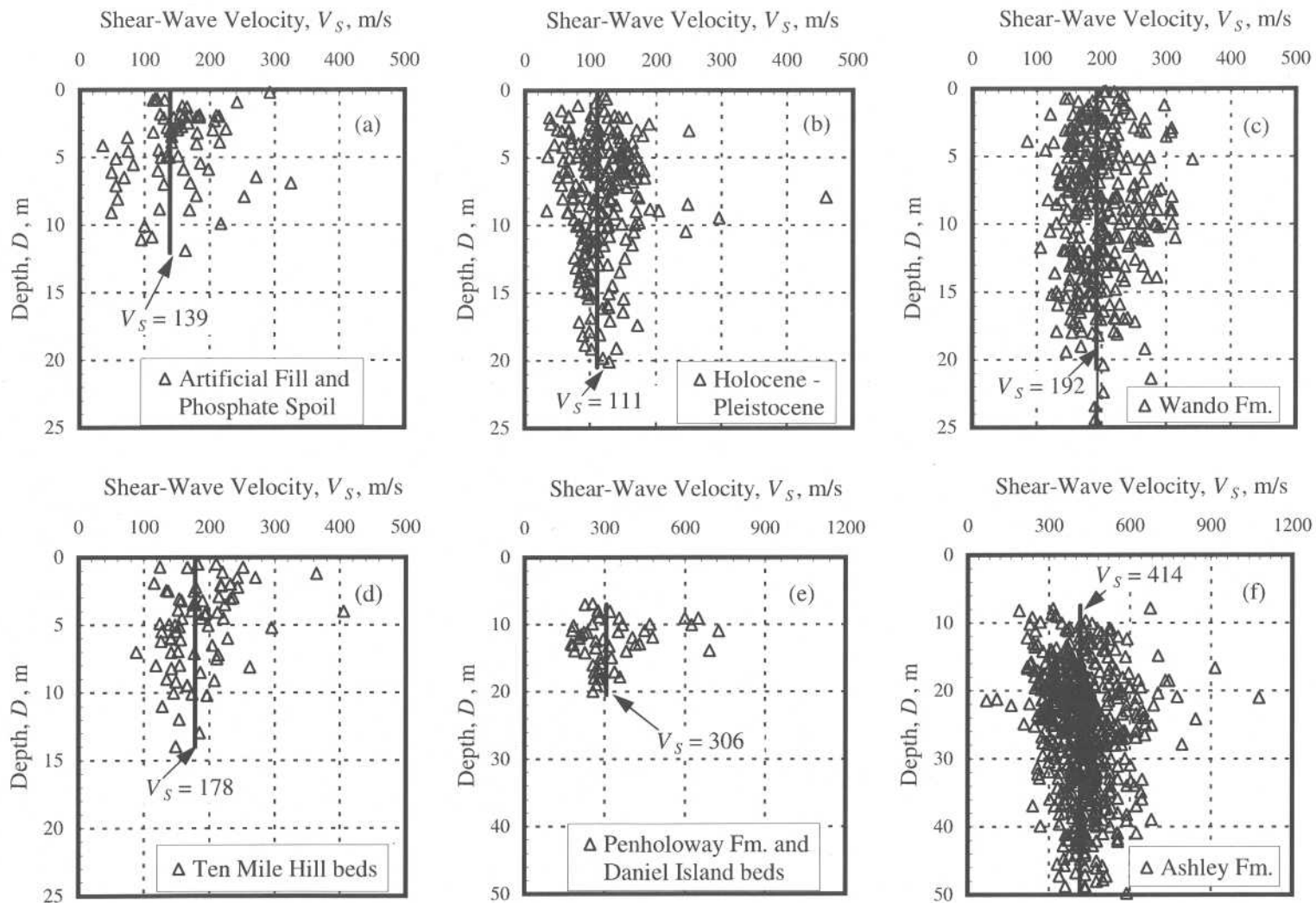


Figure 2: Compiled V_s data separated by subsurface geology - (a) artificial fill and phosphate spoil, (b) Holocene to late Pleistocene deposits, (c) Wando Formation, (d) Ten Mile Hill beds, (e) Penholoway Formation and Daniel Island beds, and (f) Ashley Formation [7].

The V_S data plotted in Figures 2(a)-2(f) exhibit little depth dependency as a whole. Therefore, to calculate average and mean values of V_S for each unit, the data are considered directly without any correction for depth.

Histograms of the V_S data from the six major geologic units are presented in Figures 3(a)-3(f). The histograms suggest that either normal or log-normal distributions can be used to represent the data. To determine the type of distribution most suitable, the chi-square test [8] is applied to the six data sets. In the chi-square test, the similarity between the considered data and the assumed distribution is evaluated by the total chi-square value, χ^2 , which is defined as:

$$\chi^2 = \sum_{i=1}^k \frac{(n_i - e_i)^2}{e_i} \quad (1)$$

where k is the number of data intervals or bins, n_i is the observed outcomes for the i th bin, and e_i is the theoretically expected outcomes for the i th bin based on the assumed distribution. Generally, it is necessary to have $k \geq 5$ and $e_i \geq 5$. Smaller χ^2 values indicate the appropriateness of the selected distribution. Higher χ^2 values imply a significant difference between the data and the assumed distribution. Thus, the distribution with the smallest χ^2 value is the most suitable distribution to represent the data.

Presented in Table 1 are the calculated values of χ^2 for the six geologic units assuming both normal and log-normal distributions. According to the χ^2 values, all V_S data sets are better represented by the log-normal distribution, except for the fill data set that is better represented by the normal distribution. Because 5 of the 6 data sets are better represented by the log-normal distribution that distribution is preferred in this study.

Listed in Table 2 are the mean values and one standard deviation ranges assuming both normal and log-normal distributions. Mean values and standard deviations for the log-normal distribution are calculated based on $\ln(V_S)$. By taking the natural logarithmic conversion of V_S values, the originally log-normally distributed data are transformed to normally distributed and corresponding parameters are obtained accordingly.

The probability density function of the log-normal distribution is given by:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln(x)-\mu}{\sigma}\right)^2\right] \quad \text{for } 0 < x < \infty \quad (2)$$

where x is the considered variable, and μ and σ are the two parameters defining the distribution. Here the variables x is V_S , and the parameters μ and σ are mean value and standard deviation of $\ln(V_S)$, respectively. The probability density functions of V_S for the six major geologic units are generated according to Equation (2) and plotted in Figures 3(a)-3(f) to compare with the histograms. It can be seen that the probability density functions match the histograms well, with the possible exception of the fill data set.

Mean values of V_S based on log-normal distribution are 139 m/s, 111 m/s, 192 m/s, 178 m/s, 306 m/s and 414 m/s for the fill deposits, the Holocene and late Pleistocene deposits, the Wando Formation, the Ten Mile Hill beds, the Penholoway Formation and Daniel Island beds, and the Ashley Formation, respectively. These mean V_S values are plotted as vertical lines in Figures 2(a)-2(f) for the depth ranges of plotted data.

The statistical results presented above can be used to generate approximate V_S profiles for sites where only the geologic profile is known. When combined with the geologic map and cross-sections of Weems and Lemon [6], the results provide required information to accurately assessed ground shaking hazard at all locations in the Charleston quadrangle.

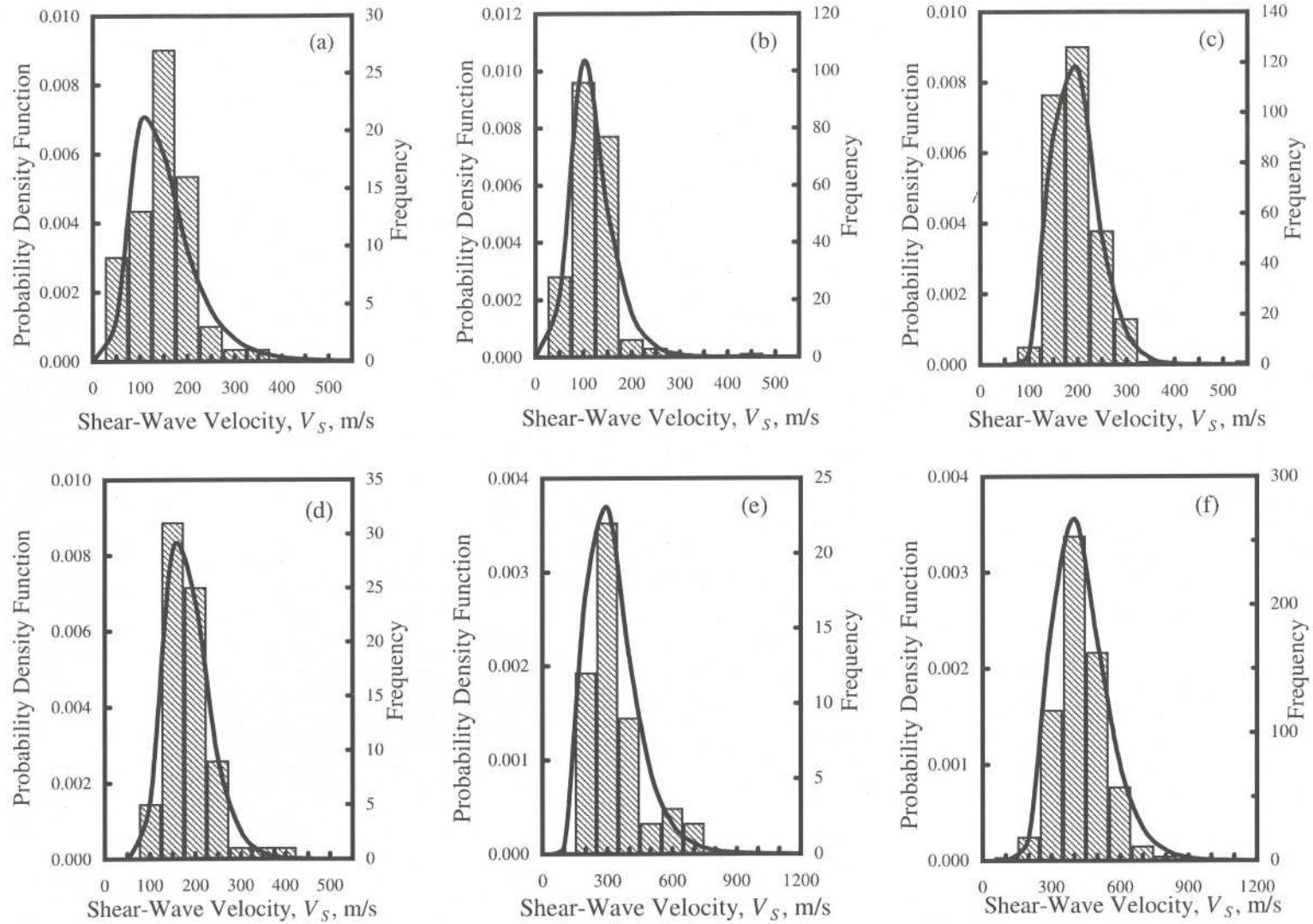


Figure 3: Distributions of V_S for six geologic units - (a) artificial fill and phosphate spoil, (b) Holocene to Pleistocene deposits, (c) Wando Formation, (d) Ten Mile Hill beds, (e) Penholoway Formation and Daniel Island beds, and (f) Ashley Formation.